U.S. Army Research, Development and Engineering Command

Development of Life Prediction Models for High Strength Steel in a Hydrogen Emitting Environment

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

ASETS Defense 2012

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Project Team

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- **ASTM F07.04 committee on Hydrogen Embrittlement**

Technical Objective

- **Increase the implementation and utilization of environmentally friendly maintenance chemicals and cadmium alternatives by alleviating the HE obstacle.**

- **FY10 – Life models for air-melted AMS 6415 4340 steel**

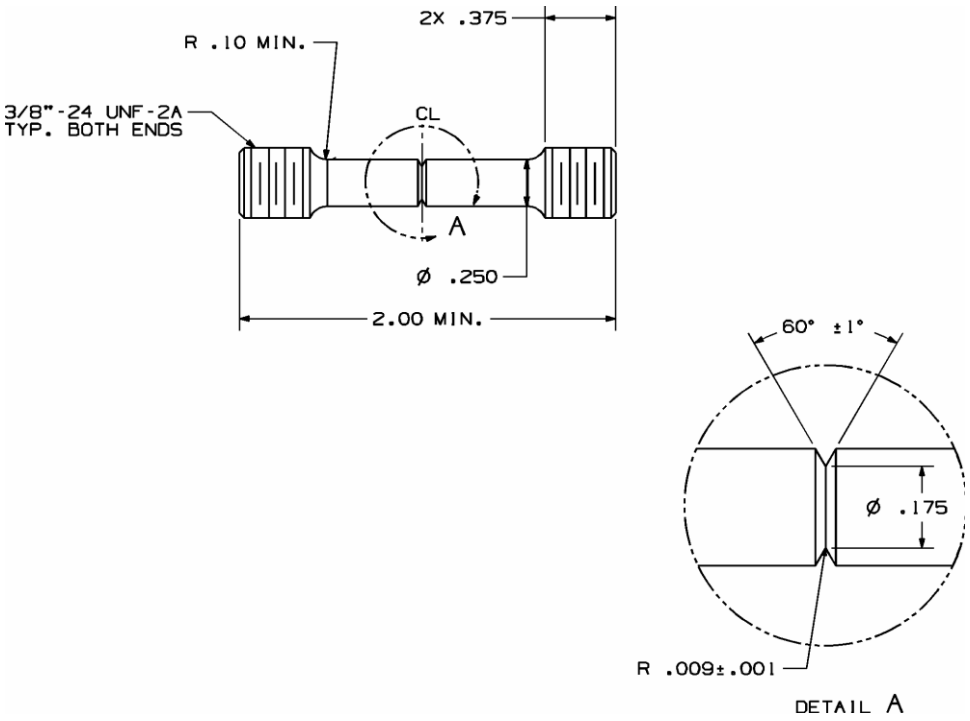
- **FY11 – Life models for aerospace AMS 6414 grade 4340 steel**

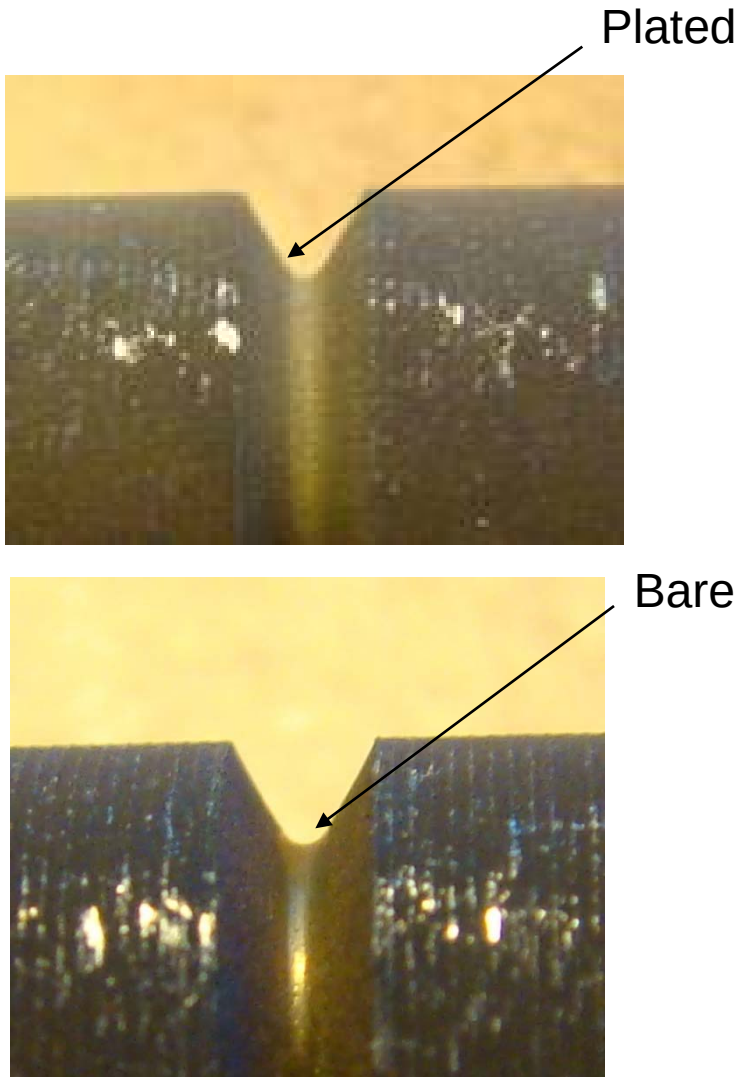
- **FY12 – Life models for prospective maintenance chemicals**

- **FY13 – Life models for prospective alternative coatings**

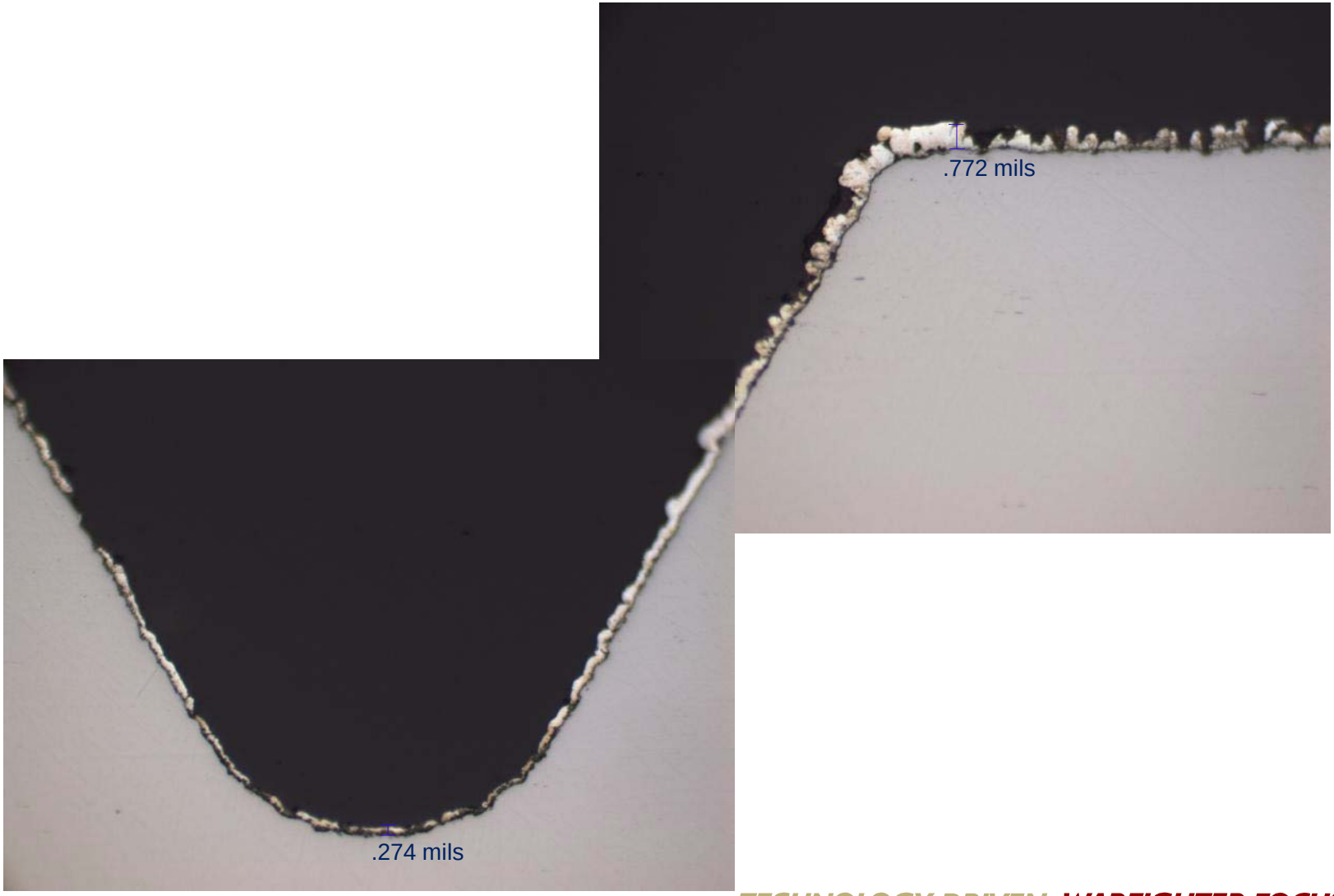
Cd Plating HE Specimens

ASTM F 519
Type 1a.1 Test Specimen



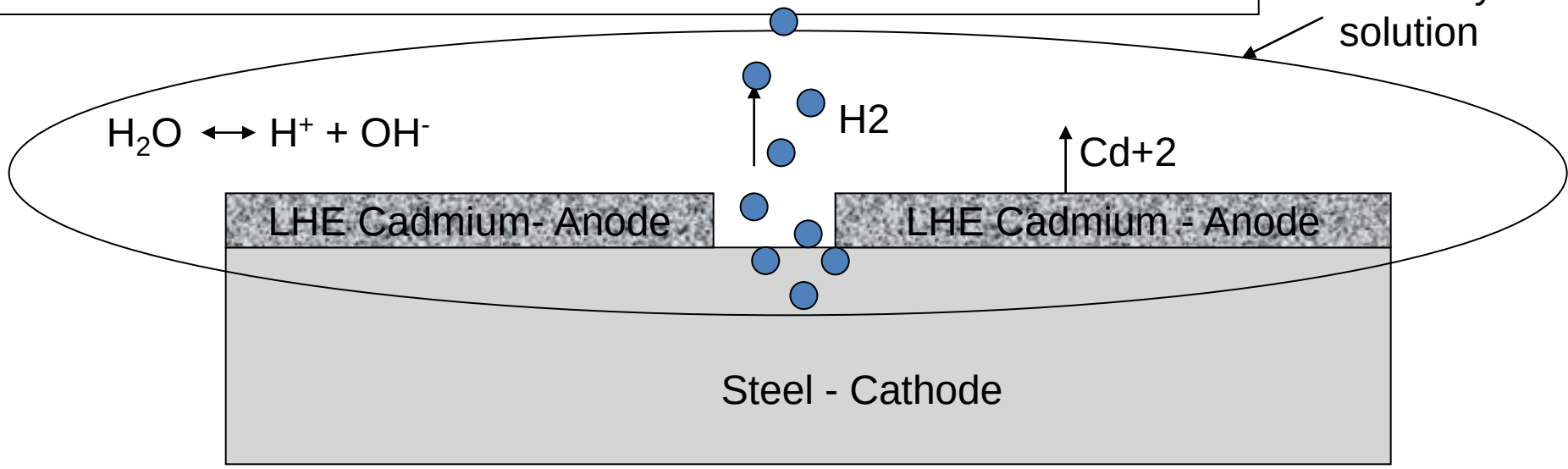


Cd Plated Notch



Cd Protection Mechanism

- **Cd is sacrificial to steel. It corrodes to prevent the steel from corroding.**



Porous Cd creates microscopic voids or thin areas that allow solutions (electrolyte) to come in contact with steel surface.
Solution forms galvanic cell between steel and Cd – the following RXNs occur:

Anode RXN at Cd: Cd → Cd+2 + 2e-

Cathode RXN at Steel: 2H+ + 2e- → H2

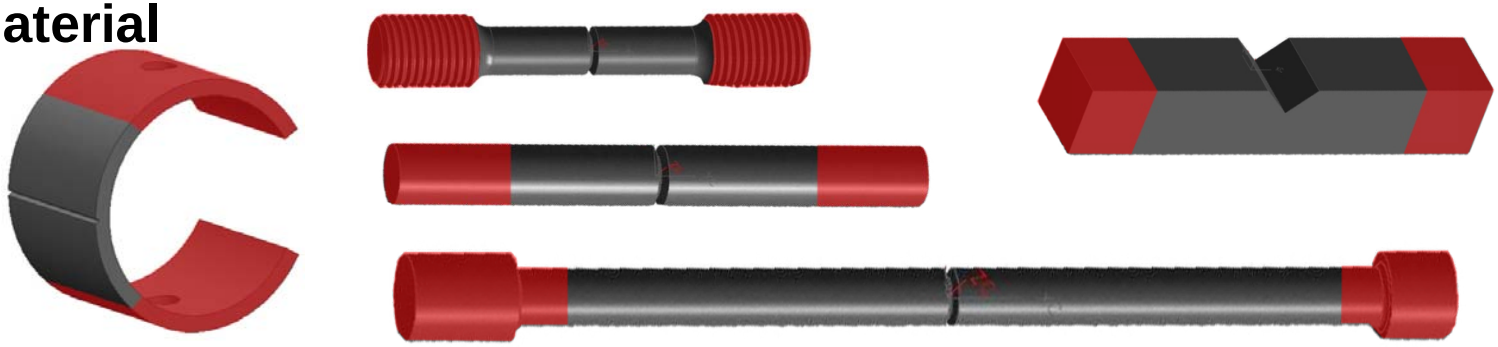
STEEL IS PROTECTED BY FORMATION OF HYDROGEN!

Re-Embrittlement Test

- 1977 – Work carried-out to develop a re-embrittlement test for ASTM F 519
  - Round Robin testing conducted by Lockheed, Douglas and Boeing aircraft companies.
  - Water used as control to determine test conditions for qualifying maintenance fluids
  - 45% NFS for 150 hours was established as a test criteria for maintenance fluids
    - LHE Cd Plated Type 1a (notch) specimens at 45% NFS will fail this test when exposed to water
      - Salt should be worse than water

Technical Approach

- **HE testing has traditionally been done pass/fail on worst case material**



- **DoE approach develops life prediction models over a range of material strength, applied stress, and environment**
  - ♦ 280 ksi
  - ♦ Stress varies with geometry
  - ♦ Cad plated steel

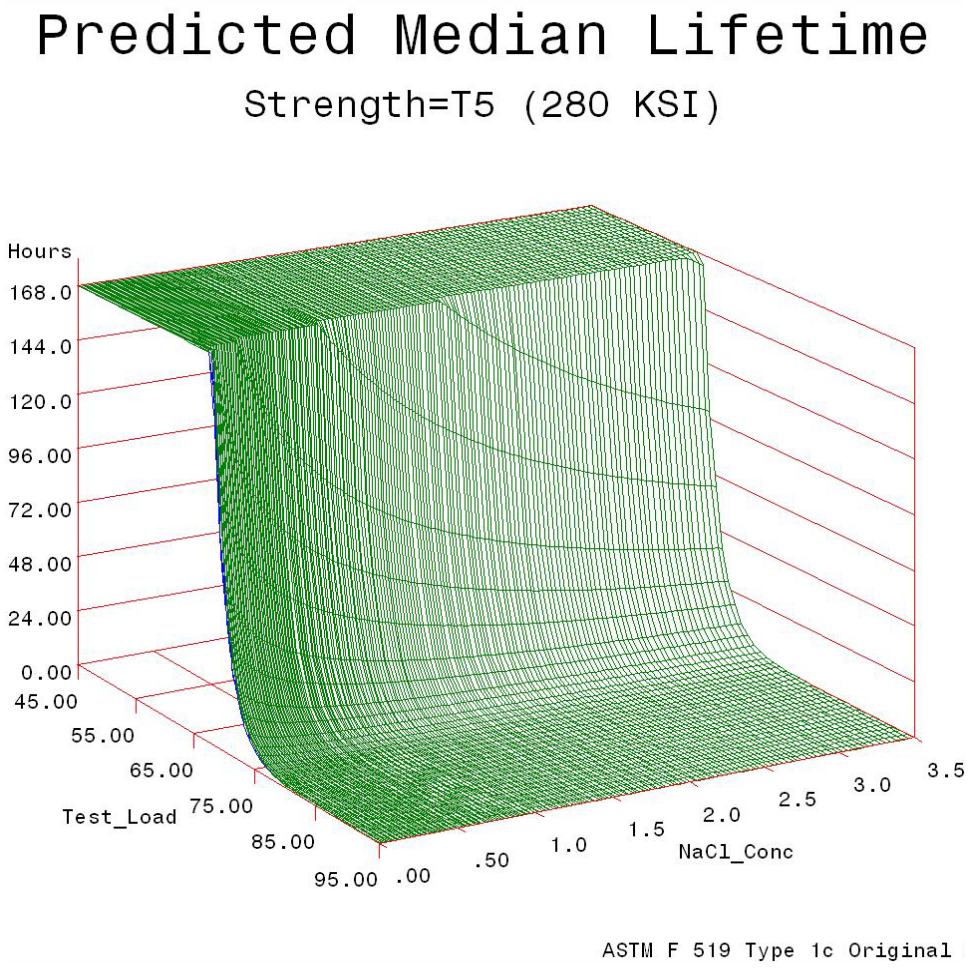
  Vs.

  - 140 - 280 ksi
  - 40 - 95% NFS
  - % of NaCl, or Conc. or Plating

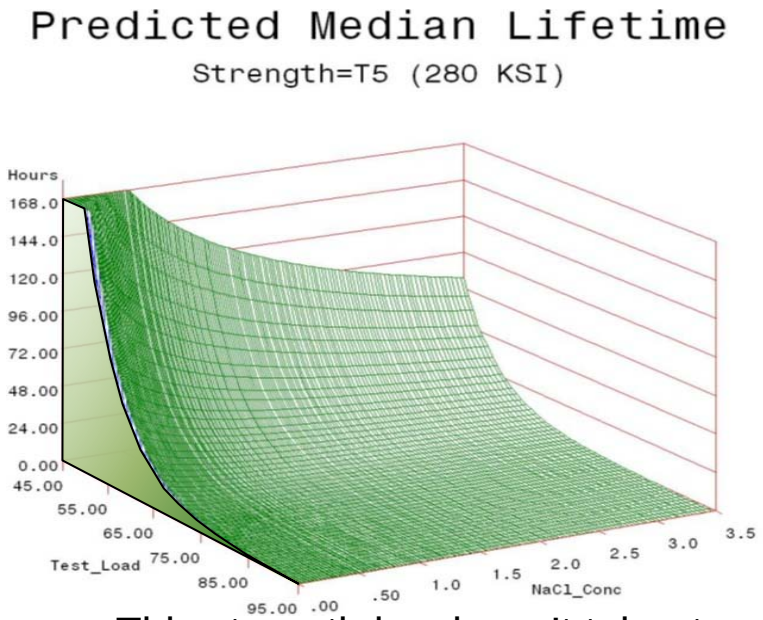
- **Statistical analysis allows a reasonable matrix size while accounting for full spectrum of variables with prediction.**
  - ♦ 5x5x5x5 (625) Vs. · 400

DoE Technical Approach

- Material Strength (140 - 280 ksi)
- Applied Stress (% of NFS)
- Environment
  - Wt.% of NaCl
  - Conc. of chemical
  - Thickness of coating
- Model Yields - TTF (Time to Failure)



Technical Approach



- Traditionally was a pass/fail evaluation
- Failure caused coatings/chemicals not to be implemented
- Models reveal safety zone (below curves)
- Data derived over a range of material strength levels

- This strength level won't tolerate greater than 50% of its UTS without the possibility of H_2 compromise from even a minimal H_2 source

- Must coat to minimize environmental corrosion, limit H_2 maintenance processes, or accept risk of failure during component life

- Empirical models help answer the common designer questions:
  - Do I need to coat for corrosion protection?
  - Can electro-chemical coating processes be safely used without H_2 fear?
  - Can I acid pickle this steel to remove scale, corrosion?
  - Will aqueous cleaners affect performance of the steel?
  - Will weld cracking be a concern once fielded?

DoE Technical Approach

Condition	-α	-	0	+	+α
Strength (ksi)	140	158	210	262	280
Test Load (% NFS)	40	45	60	75	80
NaCl Concentration (wt% NaCl)	1.25E-05	0.01	0.50	2.36	3.5

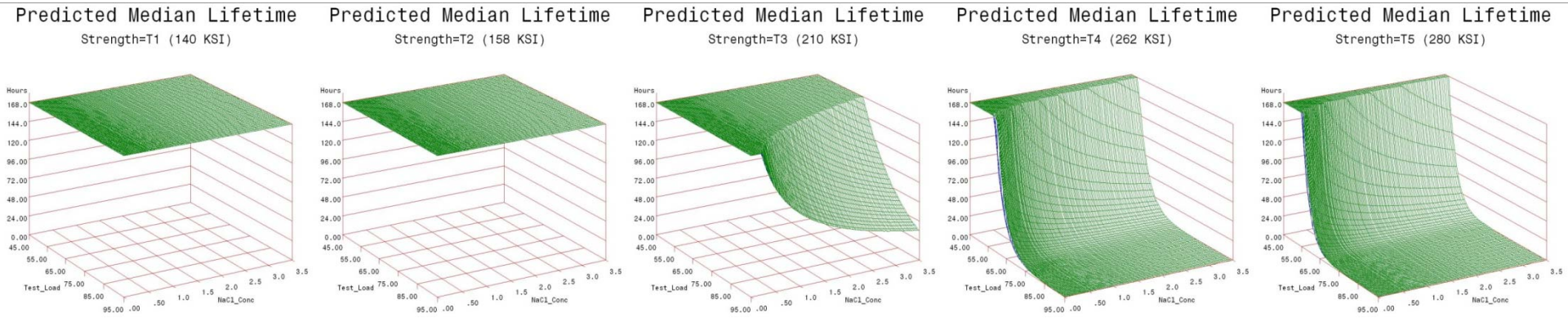
- Linear with Center points
- Quadratic
- Confirmation Runs

- Base model is developed from Linear and Quadratic portions
  - ln X =19.01 –11.67*strength -9.93*test_load -0.88*NaCl + offset
  - Run confirmations, then re-compute, then refine model

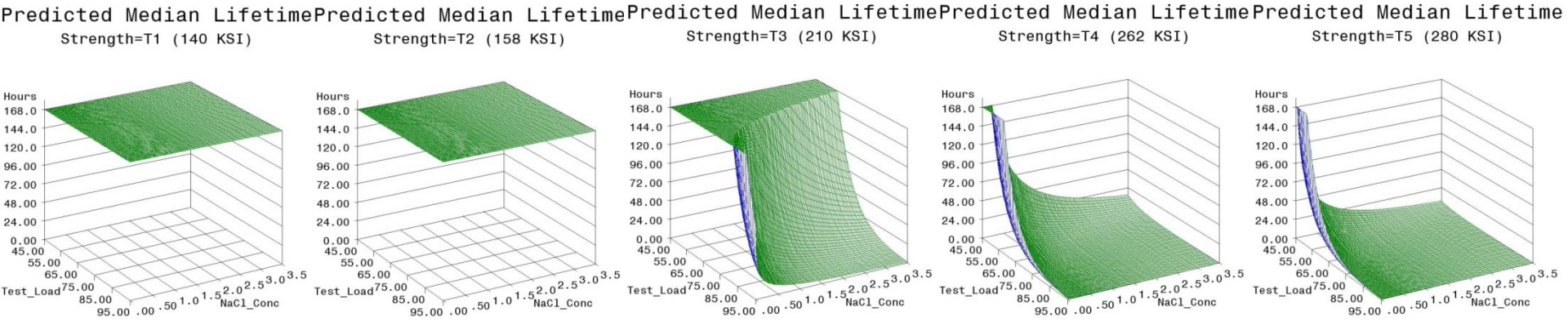
DoE Technical Approach

- Air-melt (SAE-AMS-6415), aerospace grade (SAE-AMS-6414) models were created for all geometries, heat treats, and applied stress
- Explore data to determine best geometry to assess maintenance chemicals, alternative coatings (worst case)
- Assess applicable maintenance chemicals or coatings in range of concentrations or thickness, etc.
- Results will provide the airworthiness authorities data to derive which processes (chemicals or coatings), or applications are deemed safe.

1a1 Results

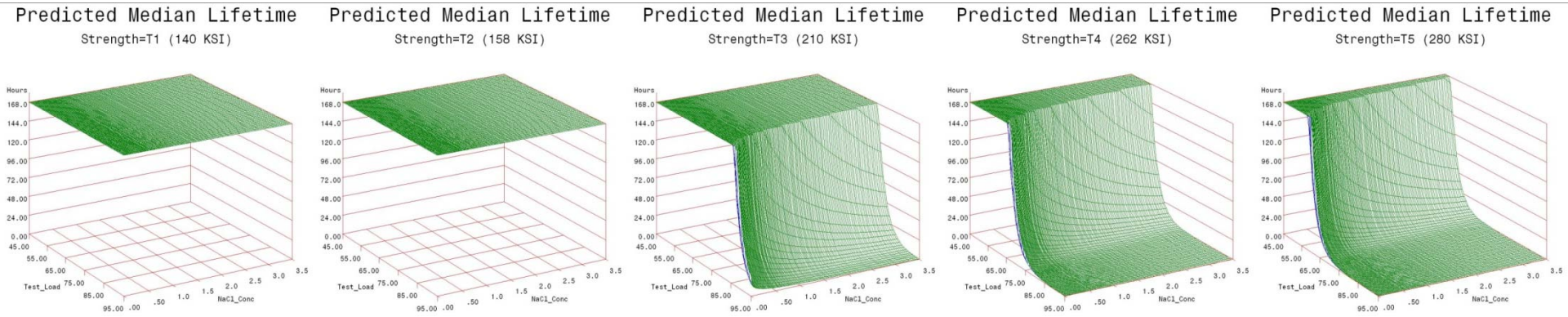


Air-melt 4340 - AMS-6415

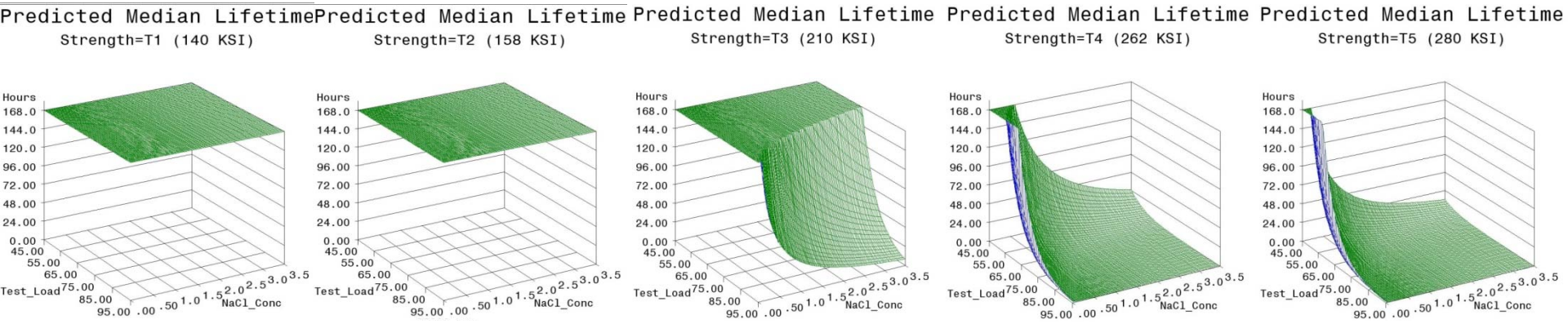


Aerospace 4340 - AMS-6414

1a2 Results

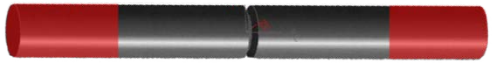


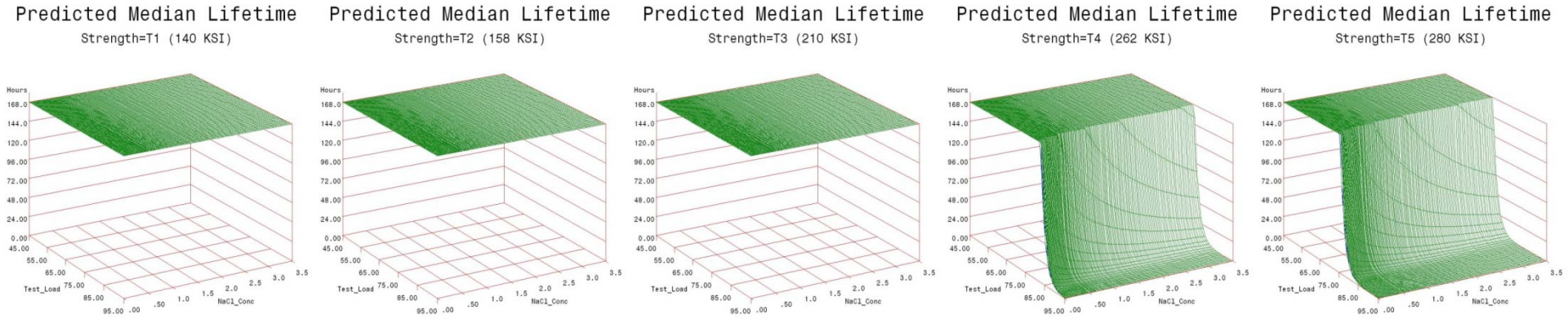
Air-melt 4340 - AMS-6415



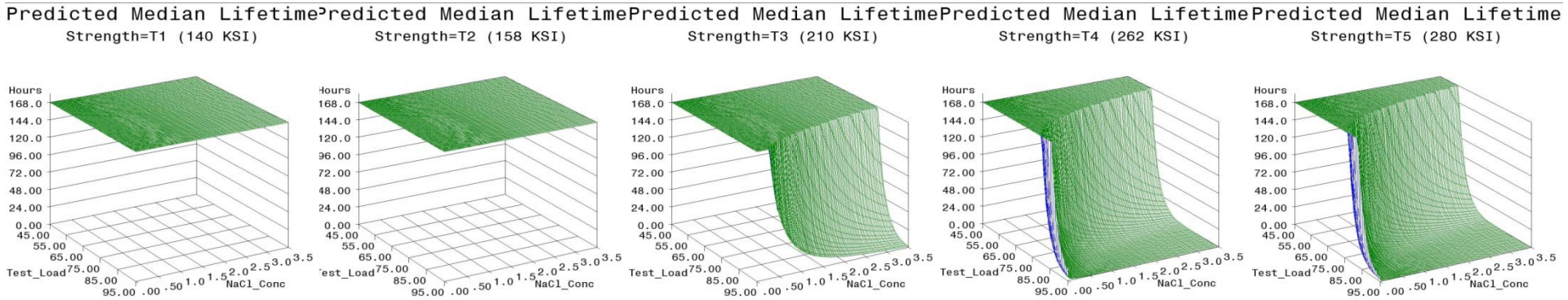
Aerospace 4340 - AMS-6414

1c Results



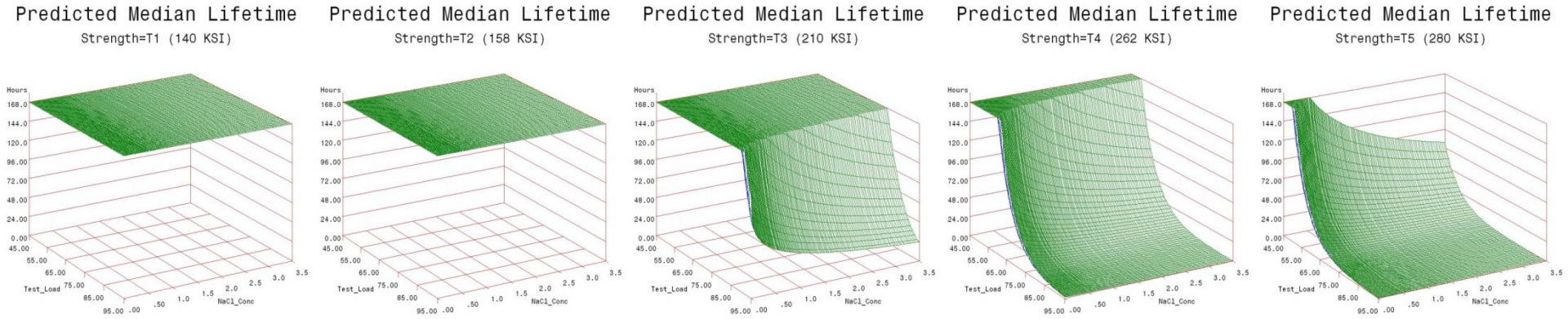


Air-melt 4340 - AMS-6415

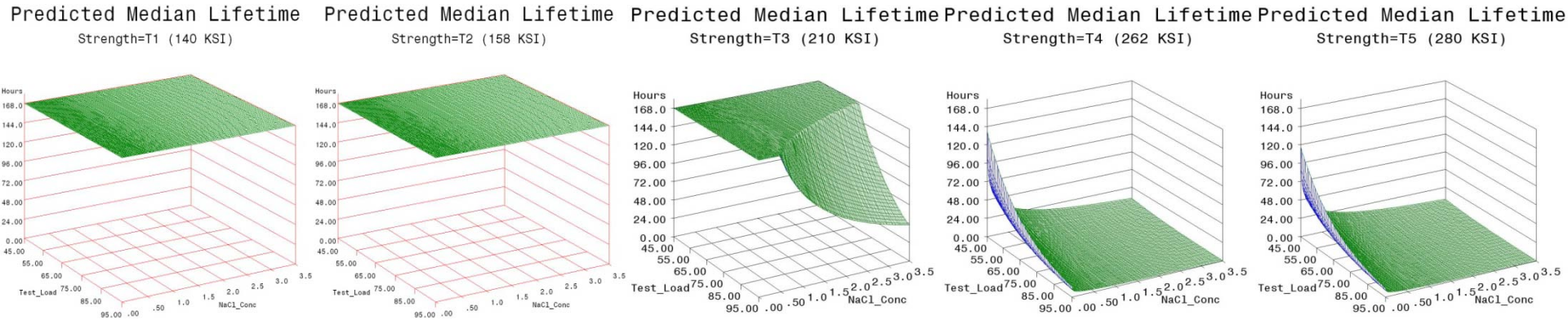


Aerospace 4340 - AMS-6414

1d Results

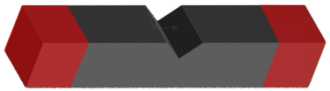


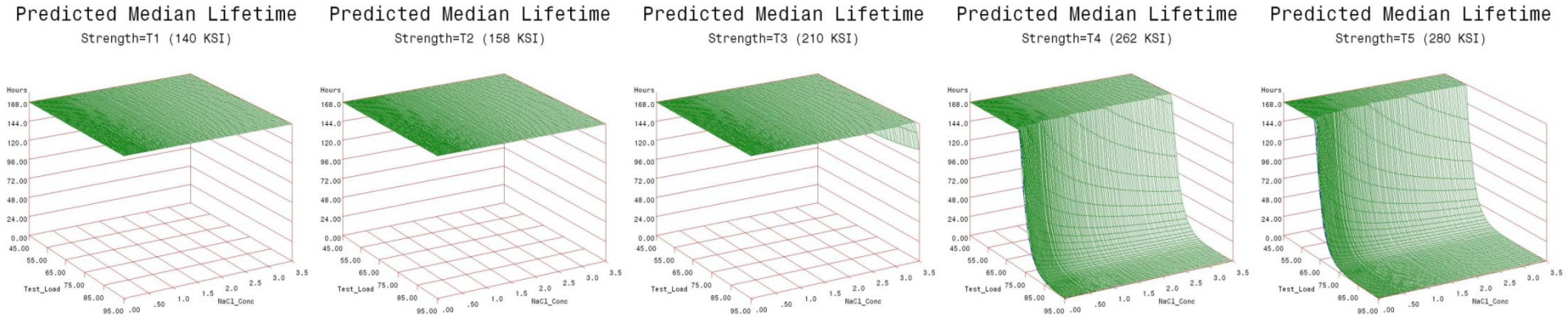
Air-melt 4340 - AMS-6415



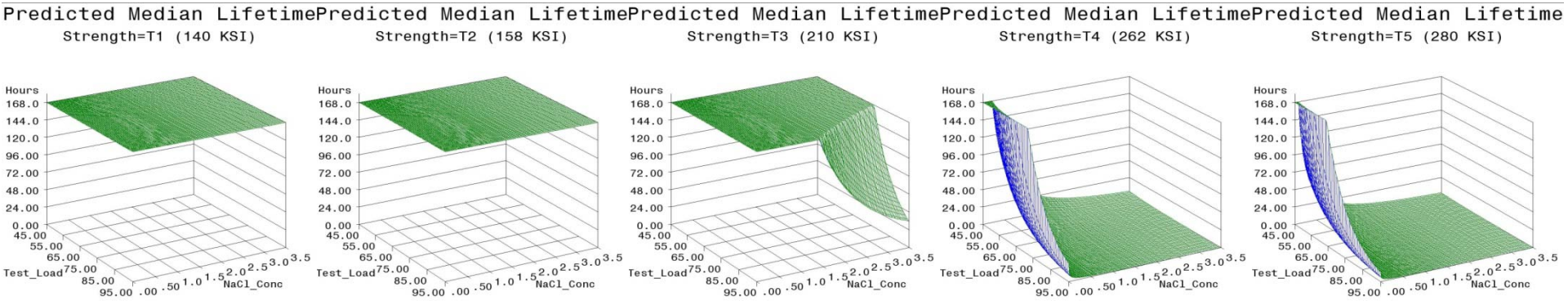
Aerospace 4340 - AMS-6414

1e Results





Air-melt 4340 - AMS-6415



Aerospace 4340 - AMS-6414

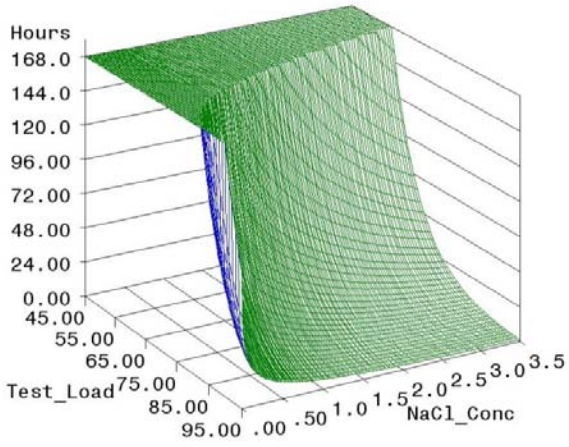
Air-melt (SAE-AMS-6415) to Aerospace (SAE-AMS-6414) Comparison

- Both demonstrate low susceptibility at or below T2 (158 ksi)
  - Even 168 hours in 3.5% NaCl not embrittling to T2 (158 ksi)
  - Environmental corrosion effects negligible below T2 (158 ksi)?
- Air-melt (lower strength at equivalent hardness) shows more tolerance
  - Not the “worst case” expected
  - Inclusions and defects absorb hydrogen
  - F519 changes needed? YES!
    - Air-melt difficult to obtain, limited use
    - Not used in aerospace
    - Doesn’t put boundary on susceptibility as intended

T3 Results-Aerospace 6414

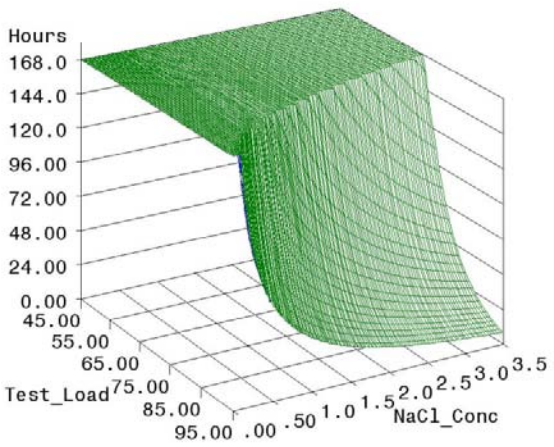
Predicted Median Lifetime
Strength=T3 (210 KSI)

1a1



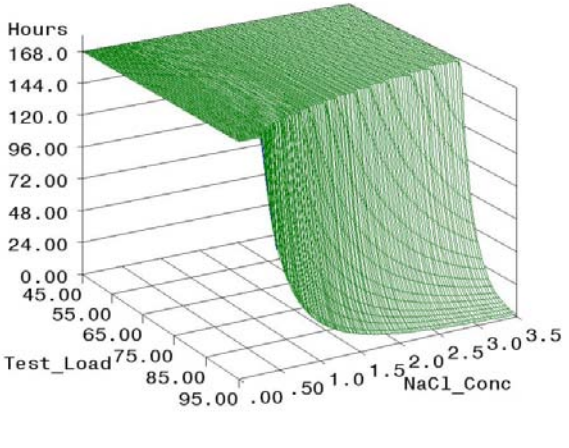
Predicted Median Lifetime
Strength=T3 (210 KSI)

1a2



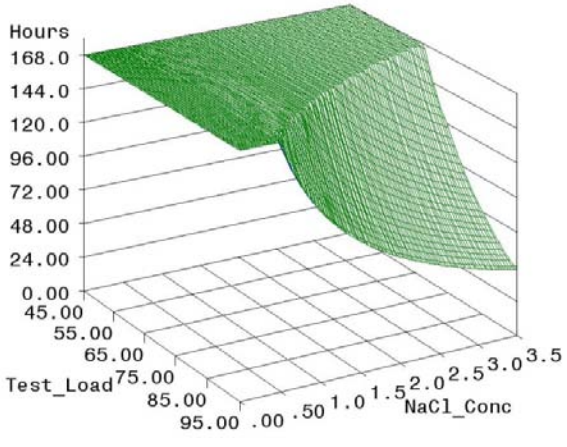
Predicted Median Lifetime
Strength=T3 (210 KSI)

1d



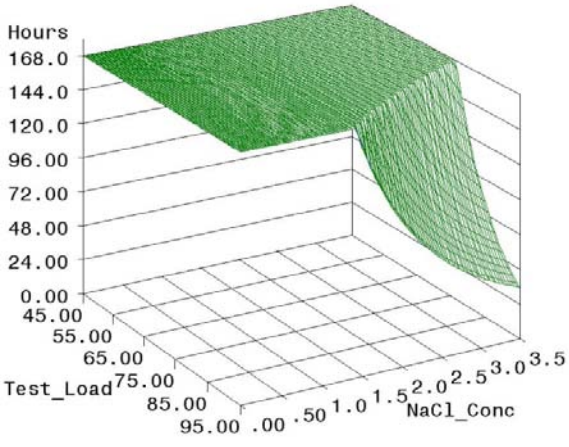
Predicted Median Lifetime
Strength=T3 (210 KSI)

1c



Predicted Median Lifetime
Strength=T3 (210 KSI)

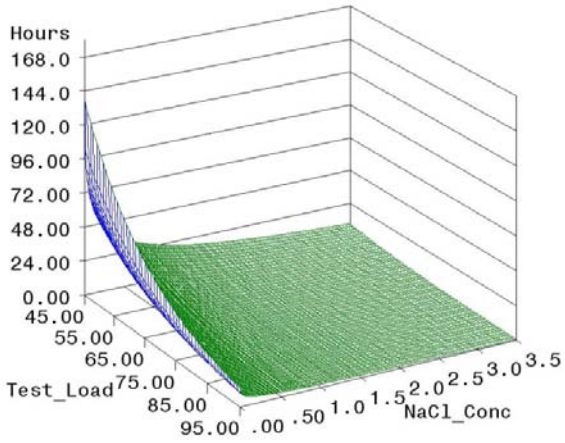
1e



T4 Results-Aerospace 6414

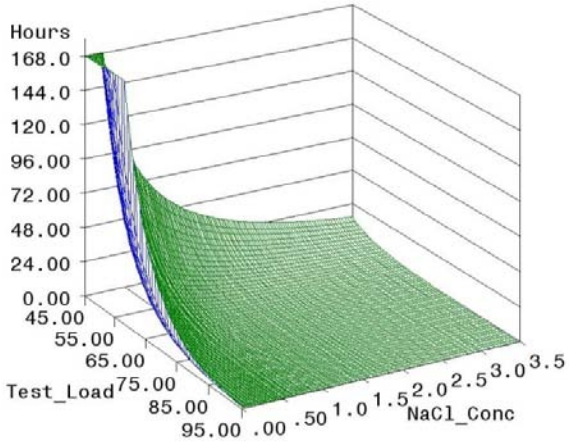
Predicted Median Lifetime
Strength=T4 (262 KSI)

1d



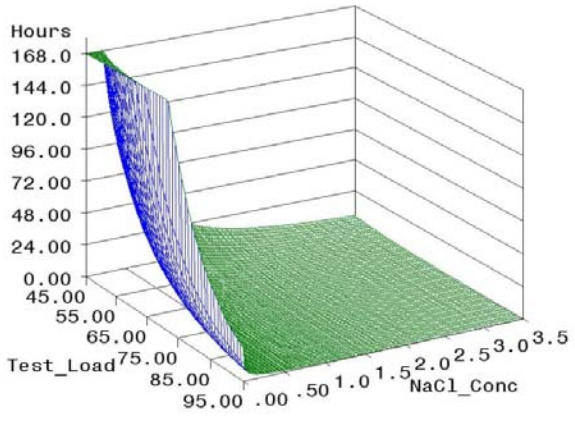
Predicted Median Lifetime
Strength=T4 (262 KSI)

1a1



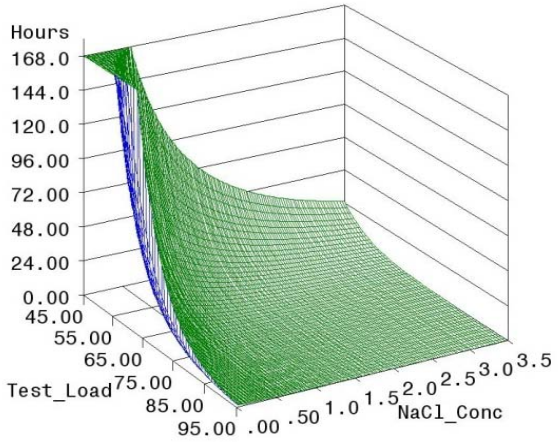
Predicted Median Lifetime
Strength=T4 (262 KSI)

1e



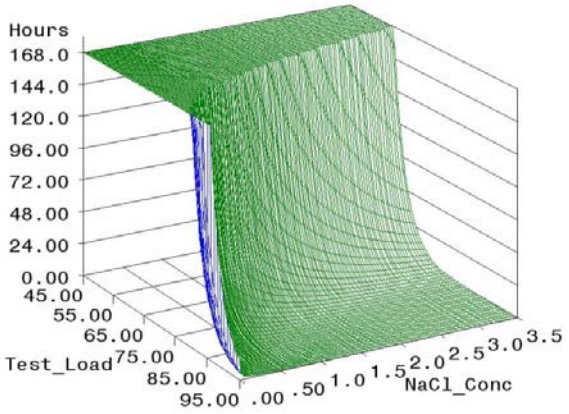
Predicted Median Lifetime
Strength=T4 (262 KSI)

1a2



Predicted Median Lifetime
Strength=T4 (262 KSI)

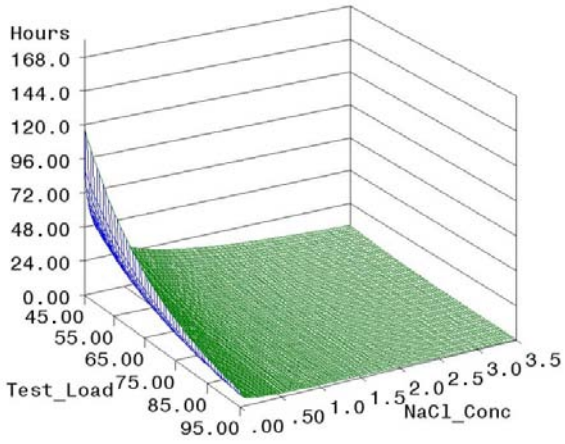
1c



T5 Results-Aerospace 6414

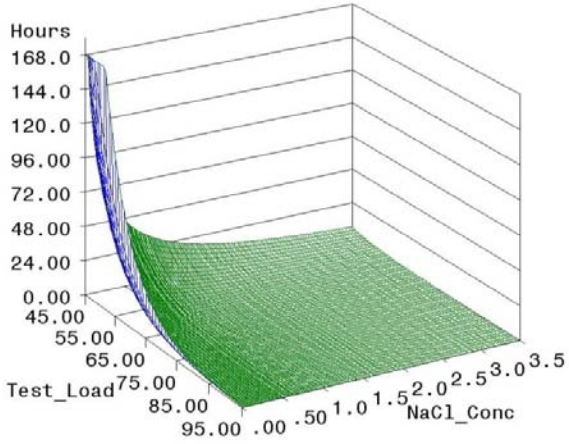
Predicted Median Lifetime
Strength=T5 (280 KSI)

1d



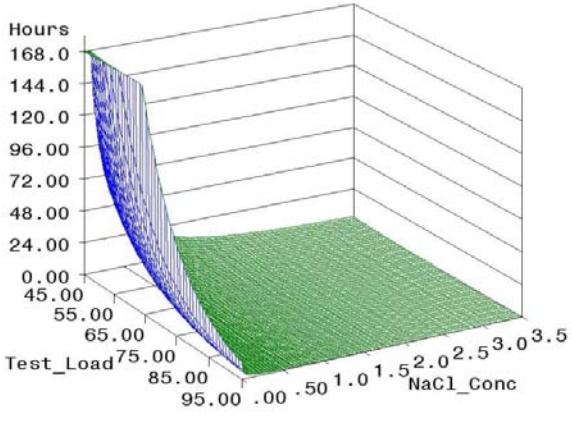
Predicted Median Lifetime
Strength=T5 (280 KSI)

1a1



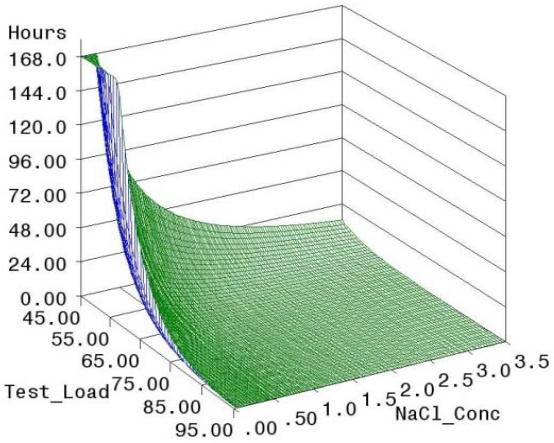
Predicted Median Lifetime
Strength=T5 (280 KSI)

1e



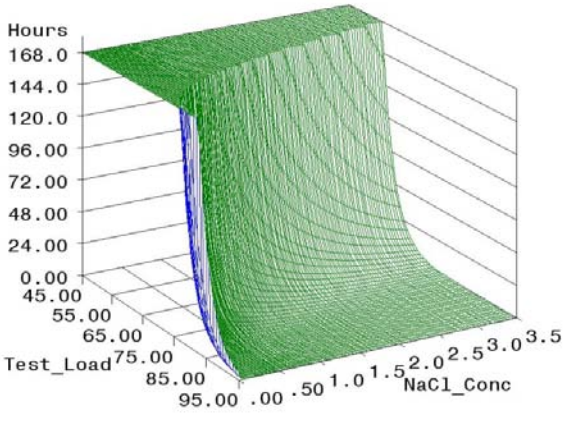
Predicted Median Lifetime
Strength=T5 (280 KSI)

1a2



Predicted Median Lifetime
Strength=T5 (280 KSI)

1c



Geometry Comparison

- All show increased sensitivity with strength, applied load, NaCl conc. as expected

- 1d geometry shows most sensitivity, 1c least

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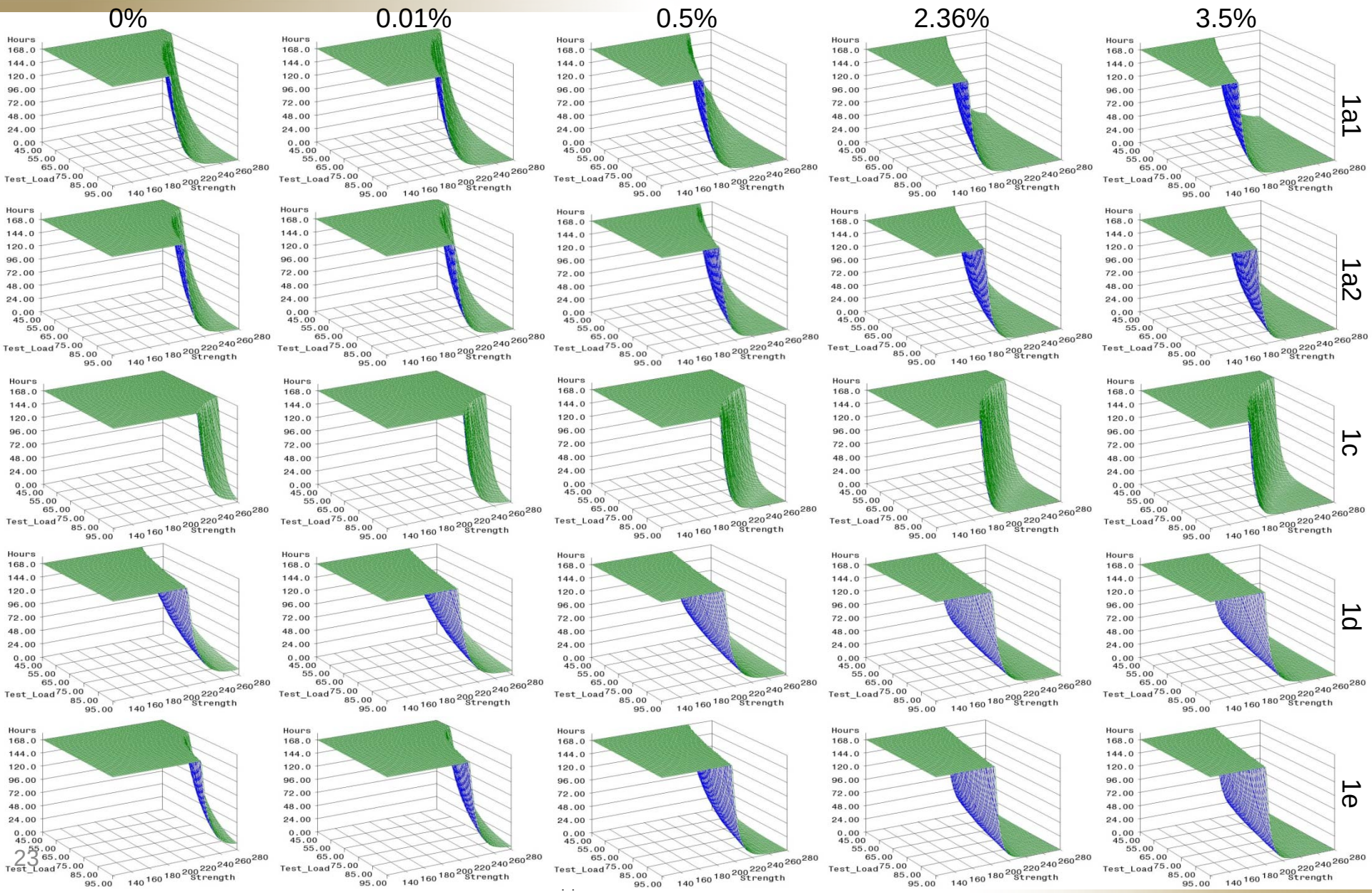
Effect of %NaCl



NaCl Concentration Effects

- Assume %NaCl = amount of hydrogen, these 3d graphs correctly showing “cliff” behavior for the threshold
  - Once H_2 threshold is exceeded, specimens break
- Even residual stresses are high enough to cause susceptibility in steels approaching 250 ksi
- 1d most uniform performance?

Transition Plan

- Work has been briefed and discussed by ASTM committee F07 on Aerospace and Aircraft, and in detail within subcommittee .04 on hydrogen embrittlement
- Most active participants of the committee are directly involved
- Changes to F-519 are likely upon completion and data review
- Lifetime prediction models for the targeted maintenance chemicals will be utilized by aviation authorities to alleviate the presently existing bake relief requirement for processes that have failed HE testing
  - Material applications below susceptibility threshold (e.g. 180 ksi)
  - Service stress applications below threshold (e.g. below 50% UTS)
- Lifetime prediction models for cadmium alternatives will be transitioned to service use for applications shown to be below the HE susceptibility threshold (e.g. ZnNi 200 ksi steel)
- Commercial partners will follow guidance from the aviation authority in implementing targeted applications deemed safe.

FY12 Plan – Aqueous Cleaners

Condition	-α	-	0	+	+α
Strength (ksi)	210	220	245	270	280
Test Load (% NFS)	35	45	60	75	90
AQ Concentration	1.25E-05	4.5	17.3	30	34.5

- Run risk reduction +/- sigma to validate appropriate test loads
- Use 1d specimen type
- Linear, Quadratic, Confirmation Runs

- Base model is developed from Linear and Quadratic portions
  - ln X =19.01 –11.67*strength -9.93*test_load -0.88*NaCl + offset
  - Run confirmations, then re-compute, then refine model